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A WATER BALANCE STUDY OF FOUR LANDFILL COVER DESIGNS VARYING IN SLOPE FOR SEMIARID REGIONS

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Abstract
The goal of disposing of radioactive and hazardous waste in shallow landfills is to reduce risk to human health and to the environment by isolating contaminants until they no longer pose a hazard. In order to achieve this, the performance of a landfill cover design without an engineered barrier (Conventional Design) was compared with three designs containing either a hydraulic barrier (EPA Design) or a capillary barrier (Loam and Clay Loam Capillary Barrier Designs). Water balance parameters were measured since 1991 at six-hour intervals for four different landfill cover designs in 1.0- by 10.0-m plots with downhill slopes of 5, 10, 15, and 25%.

Whereas runoff generally accounted for only 2-3% of the precipitation losses on these designs, similar values for evapotranspiration ranged from 86% to 91%, with increased evapotranspiration occurring with increases in slope. Consequently, interflow and seepage usually decreased with increasing slope for each landfill cover design. Seepage consisted of up to 10% of the precipitation on the Conventional Design, whereas the hydraulic barrier in the EPA Design effectively controlled seepage at all slopes, and both of the capillary designs worked effectively to eliminate seepage at the higher slopes.

INTRODUCTION

Institutional control and maintenance of low-level radioactive-waste repositories are expected to cease 100 years after the closure of a waste site, after which time the repository's engineered barriers and geohydrologic conditions need to act passively to isolate the radionuclides for an additional 300 to 500 years (US NRC, 1982). Even though the successful performance of the entire landfill is very much a function of interactive water balance processes (Paige et al., 1996), traditional remedial engineering solutions have ignored these processes, leading to numerous landfill failures (Jacobs et al., 1980; Hakonson et al., 1982). Field water balance data for landfill cover designs do not exist to enable the site operator to adequately define and engineer suitable barriers to prevent the migration of waste materials out of the landfill.

Our approach to developing an effective landfill cover technology is based on the results of ten years of individual shallow land burial studies at Los Alamos and Utah (Abeele, 1986a, 1986b; DePoorter, 1981; Hakonson et al., 1982; Nyhan et al., 1984, 1990a, 1990b). These studies were combined with current European research (Nyhan et al., 1993) to design and emplace the Protective Barrier Landfill Cover Demonstration at the Los Alamos National Laboratory in Los Alamos, New Mexico. The objectives of the present study are: (i) to determine if hydraulic and capillary barriers in three landfill cover designs can change water balance relationships over those observed in landfill covers without engineered barriers; and (ii) to determine how the slope of the landfill cover influences water balance parameters.

MATERIALS AND METHODS

Plot Construction, Design and Rationale

The Protective Barrier Landfill Cover Demonstration was constructed to compare water balance on the conventional landfill cover design, similar to that used in Los Alamos and the waste management industry for waste disposal (Jacobs et al., 1980), with that on three other designs containing engineered barriers (Fig. 1). The performance of all four designs was evaluated at dominant downhill slopes of 5, 10, 15 and 25% on plots without vegetation. These plots were installed in 1991 in our 8-ha field test facility (DePoorter, 1981) and were instrumented so that a complete accounting of precipitation falling on the plots could be measured. The plots were constructed and instrumented to provide measures of runoff and interflow, as well as seepage and soil water storage as a function of slope length.

The Protective Barrier Landfill Cover Demonstration was emplaced on an east-facing slope similar to the aspect of many of the local landfills where this technology will be applied. The area was surveyed into four pads, each of which received crushed tuff to establish the varying downhill slopes. Four 1.0- by 10.0-m plots with common sidewalls were then constructed on the center of each pad (Nyhan et al., 1993). A seepage collection system was installed in the bottom of each of the plots consisting of four metal pans filled with medium gravel (8.0- to 25-mm diam) overlain with a high conductivity MIRAFI geotextile used in previous field studies (Nyhan et al., 1990a); an 11-cm-wide space was left between the sidewalls of the plot and the pan to minimize sidewall effects.

The hydrologic properties of soils used in the field study are presented in Table 1. The soils were analyzed for porosity and for hanging column and thermocouple psychrometric moisture retention characteristics (Klute, 1986). Constant head determinations of saturated hydraulic conductivity were performed as well as pressure plate extractor determinations of moisture retention characteristics (ASTM, 1993). Van Genuchten's RETC code (van Genuchten, 1991) was

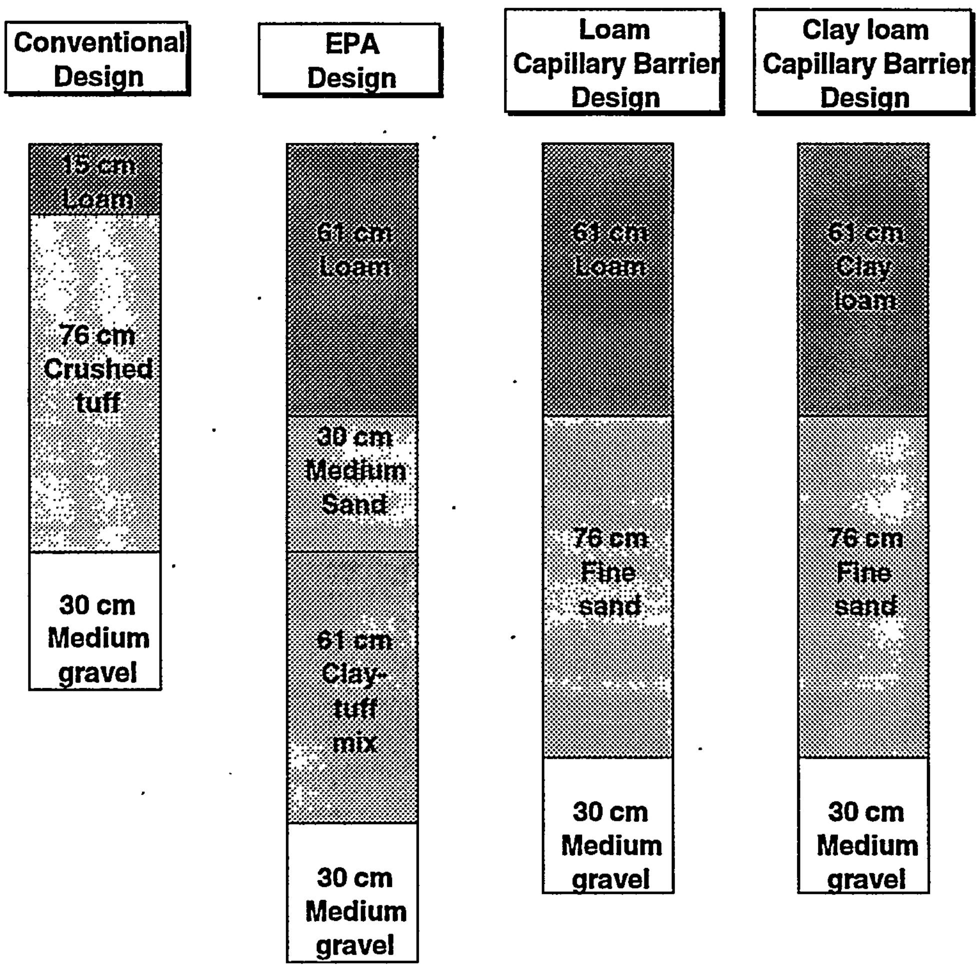

Figure 1. Descriptions of soil layers in the four landfill cover designs at the Protective Barrier Landfill Cover Demonstration. Dashed lines represent a high conductivity geotextile installed at the interfaces between soil layers.

employed to determine the van Genuchten factors for each soil using analytical procedures described previously (Mualem, 1976; van Genuchten, 1980).

The technology for controlling soil water erosion on all cover designs consisted of applying a 70% surface cover of medium gravel (8.0- to 25-mm diam). The plots with the Conventional Design, similar to that used at Los Alamos waste sites, contained 15 cm of a loam topsoil (Fig. 1) consisting of a 2:1:1 (V:V:V) mixture of an uncharacterized topsoil, sand, and aged sawdust (<9.5-mm diam). This topsoil was not underlain by an engineered barrier, only with 76 cm of crushed tuff (Nyhan et al., 1984, 1990a).

One set of plots contained the EPA-recommended (US EPA, 1989) final cover design (Fig. 1). These plots contained 61 cm of the loam topsoil described previously emplaced on top of 30 cm of a medium sand (0.25 to 0.5-mm diam. The medium sand layer corresponds to the EPA "drainage layer" and was overlain with the MIRAFI geotextile to provide the EPA-recommended filter layer necessary to prevent fine soil particles from migrating into the drainage layer. The bottom layer in the EPA-recommended final cover, called the "low-permeability layer," usually consists of a 20 mil (0.5 mm) minimum thickness flexible membrane liner (FML) on top of a 60-cm-thick layer of soil with an in-place saturated hydraulic conductivity of $<1\times10^{-7}$ cm/s. Since the plastic FML would last less than 35 years (US EPA, 1989), this feature of the EPA design was omitted in our EPA Design. The results of previous research on mixtures of local crushed tuff and sodium-saturated bentonite (Abeele, 1986a; 1986b) indicated that a 1:10 (W:W) dry mixture of finely ground Aquagel (Baroid Drilling Fluids, Farmington, NM) and crushed tuff (called the clay-tuff mixture) should easily provide the low saturated hydraulic conductivity required for this layer (Table 1).

Two designs contained capillary barriers varying only in the type of topsoil (Fig. 1). One of the designs contained 61 cm of the loam topsoil used in the previous designs, whereas the other

Table 1. Hydrologic properties of soils used in field study as determined with van Genuchten's RETC model (van Genuchten et al., 1991) and laboratory analyses.

	van Genuchten factors			θ_r	θ_s	Saturated conductivity
				(cm³/cm³)		(cm/s)
Soil description	α	n	m			
Loam topsoil	0.0271	1.539	0.3504	0.0692	0.4209	5.7×10^{-3}
Hackroy clay loam	0.0100	1.548	0.3541	0.0730	0.4839	2.5×10^{-4}
Fine sand (0.05-0.425 mm diam)	.0334	5.472	0.8173	0.0700*	0.4180	1.2×10^{-2}
Medium sand (0.25-0.5 mm diam)	0.0288	3.766	0.7344	0.0376	0.4184	1.3×10^{-1}
Crushed tuff	0.0104	1.707	0.4140	0.0031	0.4079	8.2×10^{-4}
Clay-tuff mix	0.00014	3.992	0.7495	0.0000*	0.4415	6.3×10^{-8}
Medium gravel	-	-	-	-	-	2.0

* Constrained parameter in van Genuchten model.

design contained 61 cm of a Hackroy clay loam classified as a Lithic Aridic Haplustalf (clayey, mixed, mesic family) and used in two previous studies (Nyhan et al., 1984, 1990a). These soils were emplaced on top of 76 cm of a fine sand (0.05-to 0.425-mm diam) made in the sand classifier/blender described previously. The fine sand was specifically chosen to complement the underlying medium-sized gravel in terms of optimizing the relationship between the hydraulic conductivity and the water-holding properties of the capillary barrier (Wohnlich, 1990).

Measurement of Seepage, Interflow, Runoff, and Precipitation

Runoff, precipitation, and seepage were collected year-round from December 1991 through July 1995, as well as interflow (flow occurring along the length of each plot through the medium sand layer in the EPA Design, the fine sand layer in the two designs with capillary barriers, and the crushed tuff layer of the Conventional Design). Water levels in each 100-liter tank used to collect these data were measured with a microprocessor-controlled ultrasonic liquid level sensor (model DCU-7, Lundahl Instruments, Logan, UT) connected to a multiplexed, automated system described previously (Nyhan et al., 1993). The water levels in the tanks were routinely recorded hourly, but much more frequently when the tank was either emptying or when it was nearly full. Precipitation was measured using a weighing rain gauge and a long-term event recorder.

Measurement of Soil Water Content

Soil water content was routinely monitored once every six hours from December 1991 through July 1995, at each of 212 locations throughout the 16 plots using Time Domain Reflectometry (TDR) techniques with the help of an automated and multiplexed measurement system. Volumetric water content was measured with a pair of stainless steel waveguides (60-cm long, 3-mm diam soil moisture probes; model number 6860, Campbell Scientific, Logan, UT), which are buried parallel and 5 cm apart in the soil and are connected to a 26-m length of RG-8/U coaxial cable. TDR waveguides were emplaced in the Conventional Design at depths of 5-10, 20-80, and 80-86 cm, in the EPA Design at depths of 1-61, 61-91, 96-102, and 92-152 cm, and in the two designs containing capillary barriers at depths of 1-61, 66-126, and 126-132 cm. These TDR waveguides were normally emplaced at downslope locations of 2.63, 4.65, 6.62, and 8.69 m for each soil depth, except at the deepest depths in the Conventional Design and the designs containing the capillary barriers, where they were emplaced at downslope locations of 3.64, 5.66, 7.68 and 9.70 m (to coincide with the bottom end of each of the four seepage pans installed in the bottom of each field plot).

Water Balance Calculations

Daily water balance calculations were performed by determining the daily change in soil water inventory, by summing the daily amounts of precipitation, seepage, interflow, and runoff, and then determining the amount of daily evaporation by difference. As an independent check on these evaporation estimates, evaporation was also estimated from eddy heat flux data collected from a fast-response hygrometer mounted at a height of 12 m on a 92-m meteorological tower at Los Alamos; daily values were estimated from field data collected at 15-minute intervals.

In order to further evaluate the water balance data, daily shortwave radiative energy received by field plots with slopes of 5, 10, 15, and 25% was estimated from pyranometer data collected at a height of 1.2 m from the same meteorological tower described above at the same sampling frequencies. The influences of slope and seasonality of shortwave radiative energy were calculated using the SOLARFLUX model (Rich et al., 1995).

RESULTS AND DISCUSSION

Estimates of Precipitation and Soil Water Inventory

The overall significance of each year's water balance data can best be explained by understanding the spatial and temporal occurrence of precipitation around Los Alamos (Bowen, 1990). Bowen showed that mean annual precipitation is 32.8 cm at White Rock, the only station close to the Protective Barrier Landfill Cover Demonstration with a data base longer than the data collected in this field study. We determined that 2.94-year, 5.56-year, and 20-year events occurred in 1992, 1993, and 1994, respectively.

Each of the 212 locations throughout the 16 plots was monitored for soil water content every six hours from December 1991 through July 1995. This waveform data was then reduced to soil water content data, and soil water inventory estimates were calculated for all 16 field plots.

Soil water inventory data are presented for several layers of the Conventional Design (Fig. 2). The inventory data for the loam topsoil represents the daily average readings of horizontally-emplaced waveguide pairs at a depth of 5 to 10 cm at downslope locations of 2.63, 4.65, 6.62, and 8.69 m. The frequent variations in the TDR measurements at this depth occurred because soil water content usually increased with precipitation events as small as 0.5 cm. Similar data collected at the 15-75 cm depths exhibited less frequent fluctuations because the small precipitation events did not penetrate to the maximum depths over which the measurements were integrated.

Large changes in soil water inventory were observed at both sampling depths in the crushed tuff layer monitored with time in the Conventional Design with the 5% slope (Fig. 2), typical of the changes observed on the three field plots containing this design with larger slopes. The soil water inventories presented for the 15-75 cm depth decrease throughout the summer and fall of each year and increase during the cooler winter and spring months with snowmelt additions. The data collected at the 75-91 cm depth of the tuff layer (Fig. 2) shows that soil water inventories remained at values greater than 2.9 cm (corresponding to field capacity volumetric water content of 18%) over 69% of the time. Since soil water inventory values greater than 2.9 cm for the tuff correspond to soil water regimes dominated by gravity flow, these time periods represent periods when seepage was observed to occur beneath this lower tuff layer with additions of water from upper layers.

Water Balance Summaries

The most practical comparisons among the four landfill cover designs for a semiarid region, in terms of their usefulness to the burial site operator, should be the overall performance comparison of the water balance parameters for the duration of this field study (Table 2). Using a Two-Factor ANOVA without replication ($P < 0.05$; Steel and Torrie, 1960), there was a significant effect of both landfill cover design and slope on all of the individual water balance parameters listed in Table 2.

As might have been expected in a semiarid environment, 86 to 91% of the precipitation received by all of the landfill cover designs was evaporated from these unvegetated landfill cover designs. Since the soil in the vicinity of the meteorological tower was similar to the Conventional Landfill Cover Design with the 5% slope, we were able to compare the tower hygrometer estimates of water flux with the amounts of evaporation observed in this plot and found that these two

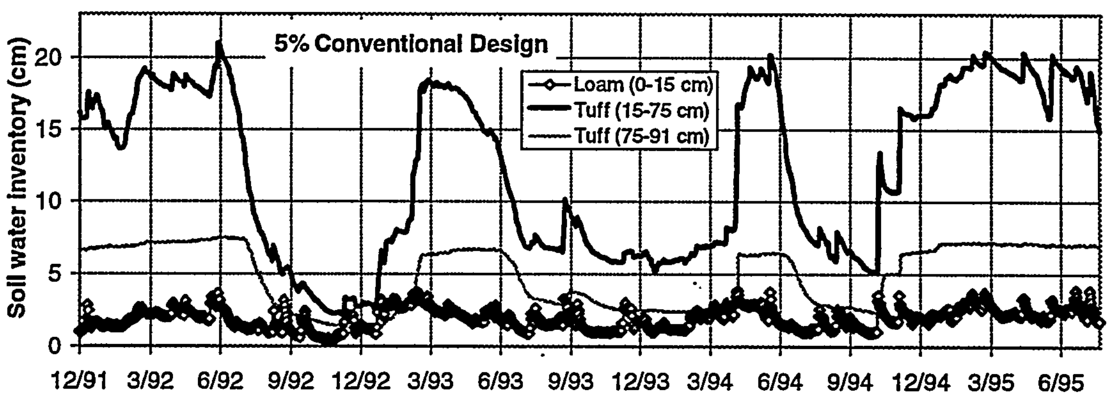

Figure 2. Daily soil water inventory as a function of time for the Conventional Landfill Cover Design with the dominant downhill slope of 5%.

Table 2. Water balance data for all landfill cover designs from December 1, 1991 through July 31, 1995. Total precipitation for this time period was 171 cm.

Landfill cover Design and slope	Water balance parameter (cm)				
	Evaporation	Interflow	Seepage	Runoff	Change in soil water inventory
Conventional Design					
5%	138.9	9.86	17.40	3.04	2.52
10%	143.8	15.12	8.16	3.19	0.45
15%	152.8	10.05	8.60	3.32	-4.57
25%	161.7	6.72	3.09	4.34	-5.69
EPA Design					
5%	154.1	17.07	0.00	1.83	-1.12
10%	154.1	16.02	0.00	1.73	0.00
15%	154.4	15.10	0.00	3.94	-2.23
25%	154.4	12.95	0.00	6.14	-2.27
Loam Capillary Barrier Design					
5%	143.0	14.59	9.64	1.41	2.09
10%	137.9	20.62	3.61	4.75	3.87
15%	150.6	17.85	0.00	3.37	-0.59
25%	155.9	10.69	0.00	5.66	-2.08
Clay loam Capillary Barrier Design					
5%	149.5	10.71	5.59	2.95	2.03
10%	152.5	12.77	0.00	4.44	1.06
15%	156.9	6.83	0.00	6.19	0.21
25%	163.7	1.50	0.00	7.43	-1.39

estimates agreed quite well. The eddy heat flux data from the meteorological tower, collected from December 1991 through July 1995, amounted to 131.1 cm water, compared with our field plot estimate of 138.9 cm water for the same time period (Table 2). For the years 1992, 1993, and 1994, the meteorological tower estimates were 36.5, 36.2, and 32.7 cm water, respectively, compared with evaporation estimates from the Conventional Landfill Cover Design with the 5% slope of 33.8, 39.6, and 34.7 cm water for the same years.

Evaporation usually increased with increases in slope within each landfill cover design (Table 2) on our east-facing study site, because plots with large slopes intercepted more shortwave radiative energy than plots with smaller slopes (Fig. 3). This effect was dominant during the first and fourth quarters of each year, during times when seepage occurred; i.e., during the fourth quarter of 1993, plots with a 5% slope received 1339 MJ/m^2 shortwave radiative energy compared with the 1561 MJ/m^2 received by the plots with a slope of 25% (Fig. 3). Consequently, the sum of the interflow and seepage usually decreased with increasing slope for each landfill cover design (Table 2).

Evaporation also varied inversely with the ability of each cover design to conduct water into the soil layers in the design (Fig. 1). The smallest amounts of evaporation generally occurred on the field plots with the Loam Capillary Barrier Design (Table 2), where water could quickly move through the loam topsoil and the fine sand layers, which had saturated hydraulic conductivities of 0.0057 and 0.012 cm/s, respectively (Table 1). Slightly larger amounts of evaporation occurred on the plots with the Conventional Design than on those with the Loam Capillary Barrier Design, because water had to move through the loam topsoil in the Conventional Design, but then

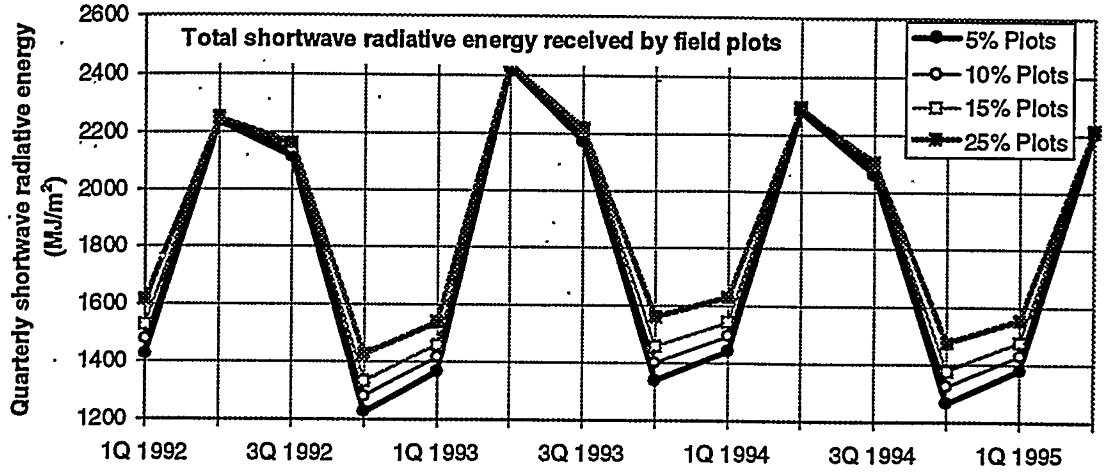

Figure 3. Quarterly total shortwave radiative energy received by field plots with slopes ranging from 5 to 25%. Data estimated from 15-minute meteorological tower observations that were corrected for slope using the SOLARFLUX model (Rich et al., 1995).

migrated more slowly through the crushed tuff layer which had a saturated hydraulic conductivity of 0.00082 cm/s (Table 1). The plots with the EPA Design and the Clay Loam Capillary Barrier Design generally had larger amounts of evaporation than the plots with the other designs, because of the low saturated hydraulic conductivities of the clay/tuff mix in the EPA Design and of the clay loam topsoil in the Clay Loam Capillary Barrier Design.

Although runoff did not seem to be related to surface slope on a per event basis, runoff did increase with increasing slope over the 44-month duration of this study for each of the designs. Runoff generally accounted for about 2-3% of the precipitation losses across all of the plots studied (Table 2).

The site operator usually prefers minimal seepage to occur on the landfill. Seepage was definitely decreased with engineered barriers in this study over that observed in the Conventional Design, which did not contain an engineered barrier. Although 9.86 cm of interflow occurred on the Conventional Design with the 5% slope, 17.4 cm of seepage occurred over the life of the field study. The hydraulic barrier in the EPA Design effectively controlled seepage at all slopes, and both of the capillary designs worked effectively to eliminate seepage at the higher slopes (Table 2), many of which are commonly used on waste sites at Los Alamos and throughout the waste management community.

Current state and federal regulations usually require an engineered barrier to be present in the landfill cover design, a design criterion that is also impacted by risk assessments and cost considerations. Capillary barriers can be used as alternative designs to the EPA Design (US EPA, 1989), with the realization that seepage did occur at 5 and 10% slopes in the Loam Capillary Barrier Design and in the Clay Loam Capillary Barrier Design with a slope of 5% (Table 2). Although the EPA Design does seem to eliminate seepage in field plots with 5 and 10% slopes (Table 2), the EPA design is probably more expensive than alternative designs (Paige et al., 1996). In the case of either engineered barrier, other field data sets similar to that collected in the current study are needed in a variety of climates and with slope lengths longer than 10 m to validate hydrologic models that can be used in design selection.

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